Solution Mining

To

Milt and Dad

for teaching extractive metallurgy science
and mineral engineering practice,
and pointing the way

PREFACE

This text is derived from a course in solution mining taught to metallurgical and mining engineers at the University of Idaho. The course was initiated to provide an introduction to the rapidly expanding field of solution mining, particularly for the extraction of gold, silver and copper. The annual economic value of solution mined metals in the United States now exceeds that of metals extracted by underground mining. But solution mining is a relatively new field, at least at its present scale. It has not been part of the established academic curricula and has been taught only as an elective subject at a few institutions and in short courses given off campus.

Although several solution mining symposia proceedings have been published in recent years, primarily by the Society of Mining, Metallurgy and Exploration, an integrated text with problems suitable for undergraduates, practicing engineers and geologists was not available. Keeping in mind this broad audience spectrum, the book has been designed to require only a preliminary understanding of basic inorganic chemistry. Although mathematical modeling has made contributions to understanding solution mining phenomena, it is eschewed somewhat in the interest of a wider audience of practitioners, except for chapter 12.

I first became interested in solution mining in 1971 after spending a summer at Lawrence Livermore Laboratory (LLL) where a large pilot plant scale pressurized leaching experiment was underway to experimentally simulate copper extraction by flooded leaching at depth. Livermore was then pursuing peaceful uses of nuclear explosives, and investigating in situ rubblization of ore using nuclear explosives prior to leaching. Experimental results were explained by a computer simulation model published in 1972. Before that I had been stimulated by Prof. Milton Wadsworth, while a student at the University of Utah.

During summers of the early 1970s, I solution mined gold contained in low-grade ore heaps left from a previously operated Nevada gold mine. Since then, heap leaching gold ore has become a billion-dollar industry in Nevada.

From 1973 to 1978, as manager of hydrometallurgy at the Kennecott Research Center in Salt Lake City, I participated in major laboratory and mine site experiments to better understand copper leaching from mine waste dumps. This major source of domestic copper production involves many interrelated complex phenomena, and the Kennecott research during this period (subsequently released) was the most extensive yet conducted on this important aspect of metal solution mining.

Ore testing of precious metal deposits returned to the fore during the 1980s, along with studying the solution mining of borates, while I was directing the Anaconda Minerals' Tucson Research Center. Recently, I have been interested in biooxidative pretreatment of low-grade refractory gold ores in bacteria inoculated wet stockpiles, prior to cyanide heap leaching.

I am indebted to many colleagues over a span of more than twenty years for the experiences, ideas and friendships shared during our mutual interest in solution mining. Principal among these are Jay Agarwal, John Apps, Roshan Bhappu, Bob Braun, Al Bruynesteyn, Larry Cathles, Don Davidson, Jerry Fountain, Joe Harrington, Rudy Jacobson, Jonathan Jackson, Bill Larson, Art Lewis, Ed Malouf, Dave Milligan, Keith Prisbrey, Bruce Ream, Dave Reese, Ken Richards, Ron Roman, Joe Schlitt, John Sibert, Rush Spedden, Dirk Van Zyl, Milton Wadsworth and Rolf Wesely.

I am especially grateful to Joe Schlitt, Milt Wadsworth and the late Don Davidson for careful reviews of the first-edition manuscript and many useful suggestions. Rudy Jacobson, Milt Wadsworth and David Dixon were helpful with this new edition.

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ONE

Introduction

SCOPE OF SOLUTION MINING

Solution mining is variously defined. In this text it includes all forms of extraction of materials from the earth by leaching and fluid recovery, both by *in situ* methods and heap leaching of excavated ore. The emphasis is on minerals, brines and other naturally occurring solutions, but the theory and practice developed for these materials can be extended to contaminants introduced into the earth by human activity. Several minerals are readily soluble in water, forming brines, and recovery of these fluids represent the earliest applications of solution mining. Extraction of solid minerals by an aqueous solution flowing through and **leaching** (dissolving) them from their host rock has become of increasing importance in solution mining. This includes both readily soluble **evaporite** minerals and metallic **ore** minerals requiring leaching reactions with acids or other chemical lixiviants and, often, oxidation of the mineral. In outlining the scope of solution mining in this introductory chapter, some words will be contextually defined as they are conventionally used in solution mining practice.

Solution mining is an interdisciplinary field involving geology, chemistry, hydrology, extractive metallurgy, mining engineering, process engineering and economics. A few of the factors to be considered in solution mining projects are: leaching chemistry, rock (gangue) chemistry, solution flow in the ore mass, air flow in the ore mass (percolation leaching), open void space in the ore mass available for flow, ore (rock) microporosity, transport within dead end micropores by ordinary chemical diffusion, metal/mineral recovery technology and operations and their affect on

leaching extraction, environmental containment, solution losses, brine chemistry, solar evaporation pond engineering and reclamation.

The approach of this text is to include description, theory and practical aspects of current solution mining technology. Principles will be integrated with specific metal/mineral systems and practice, beginning with simple systems and proceeding toward increasing complexity. Understanding the important factors, their relationships with each other and their influence on the technological and economic outcome are not sacrificed to detail. Mathematical modeling of solution mining systems should aim at providing improved understanding of these complex phenomena rather than at numerical certitude.

At the present time water is the only solvent base of commercial interest, with the exception of molten sulfur recovered using hot water in the Frasch process, so this text's discussion will be focused on aqueous systems. Generally the principles are transferrable. In situ or "true" solution mining involves extraction of minerals from the undisturbed ore in place. Leaching the ore rubblized within the ore body is sometimes referred to as "modified in situ" solution mining. Excavation of the ore using conventional mining methods followed by heap leaching in prepared ore stockpiles on the surface and dump leaching of mine overburden (waste) are important applications of solution mining that will be covered in this text. The extraction operation (leaching, brine recovery, etc.) is coupled with a metal/mineral separation operation, nearly always on the surface and adjacent to the extraction operation, for separation of the dissolved metals or minerals from the recovered fluid solution or leachate. Large volumes of solution circulate between the extraction and separation operations. Both gravity flow and pumping are used to transport the leaching fluids. Leachates generated by the extraction operation are often referred to as "pregnant solutions" or pregnant liquors, while fluids being returned to the extraction operation are often referred to as "barren solutions" for obvious reasons. Sometimes solution is bled from the otherwise closed circulating solution to control the accumulation of undesirable impurities. This text will focus on extraction operations and will either omit or only peripherally include mineral and metal recovery from solutions. The science and engineering of metal separation technologies are described in hydrometallurgy texts including Habashi (1980) and Van Arsdale (1963).

Sufficient permeability in the ore mass to permit solution flow is an important, and often restricting, factor in solution mining. In situ leaching must rely upon open void space or natural fractures in the ore for solution flow paths. Sandstones and vuggy evaporites are often sufficiently

open to provide good permeability. Evaporites contain large amounts of soluble mineral and therefore tend to become more open as extraction proceeds.

Many metallic minerals were deposited by geochemical processes that involved hydrothermal solutions flowing in natural rock fractures. If these fractures remain open, they can be a source for extraction by solution mining. However, host rocks for sulfide ore deposits typically contain fractures with a microporosity of only about 1–6% and very low permeabilities—often too low for commercial production rates in solution mining. Also, major fractures are a source of high flow channels that short-circuit the solution, not allowing it to sweep uniformly through most of the ore mass. This leads to low sweep efficiency, low yield of extracted metal/mineral, and often economic failure. Furthermore, the uncertainty in sweep efficiency causes uncertainty in economic forecasting, which prevents many solution mining projects from being implemented. Not only adequate permeability but fairly uniform permeability is required.

Success often requires a substantial increase in permeability by fragmenting the ore in place, rubblizing. Effective fragmentation nearly always requires a substantial increase in volume, 15–20%, to provide open space for flow channels. Planned deliberate caving, blasting and natural subsidence over underground excavations and abandoned mines are ready sources; the overlaying subsidence provides a large volume of broken ore. Leaching caved cappings over otherwise depleted underground mines is a common application of solution mining.

Both flooded leaching and percolation leaching, or trickle leaching, are employed in solution mining. Flooded leaching pertains to situations where the ore mass is saturated with the solution; usually only one fluid phase is present and the operation typically occurs below the water table, or the solution is otherwise contained. Flooded leaching has many flow characteristics in common with ground water flow. The mathematical treatment and numerical models describing flow problems in hydrology are often readily transferrable. Percolation leaching involves downward flow of unsaturated solution by gravity; two fluid phases, solution and air, are always present within the ore mass. Other distinguishing characteristics of percolation leaching and flooded leaching are presented in Table 1.1. Many aspects of solution mining are treated in the Mining Engineering Handbook (2nd edition, 1992).

Environmental containment of solution must always be maintained in a solution mining operation, and various approaches to achieve this will be discussed in the text. Remediation of contaminated ground and water, including groundwater, is covered in the last chapter.

Table 1.1   Characteristics of Percolation and Flooded Leaching.

PERCOLATION LEACHING

– Solution trickles downward by gravity in an adequately permeable ore mass while dissolving the valuable mineral(s)

– Solution must be uniformly spread over the top of the ore mass and collected at the bottom of the ore mass, over an impervious bottom layer to prevent further downward percolation

– Adequate permeability is usually achieved by fragmentation from mining and/or by additional ore crushing. Excessively fine or clay-like ore with low permeability may be **agglomerated** to improve permeability

– The solution is not saturated and air is present, which may or may not be important to the leaching chemistry; if oxygen is consumed the air may be partially oxygen depleted

– Important applications are heap leaching gold, silver, copper, and uranium; copper mine waste dump leaching; leaching mine subsidence for copper and uranium

FLOODED LEACHING

– Solution flows because of a pressure gradient, often from an injection well(s) to a production well(s), through an adequately permeable ore mass

– Air is not normally present, although injection of air or oxygen as a chemical reactant bubbling upward through the otherwise solution saturated ore mass may occur; this is an example of **two-phase flow**

– Leaching occurs only below a water table, either natural or artificially induced

– The permeability must be nearly uniform to provide good sweep efficiency and extraction; the ore zone must be bound by ground of substantially lower permeability to contain solution flow

– Important applications are brine production from wells, leaching uranium and copper (presently limited but of considerable experimental development) below the water table

Solution mining to produce brines is applied to both buried and surface evaporites and is a major source for the production of numerous water soluble salts and minerals, including common salt (sodium chloride), potash, magnesium, lithium, trona (sodium carbonate), and boron minerals. Sea water, natural playas (salt lakes) and underground brines are all important sources of mineral bearing solutions. **Solar pond evaporation** is an important and relatively inexpensive method of concentrating brines before entering a mineral recovery or separation plant. Often several salts are separated and recovered from complex brine mixtures.

Several industrially important metallic minerals are not soluble in water or natural brines but are soluble in aqueous chemical solutions, which are used to extract them in solution mining operations. Oxidized minerals of

copper and uranium are soluble in acidic solutions at a sufficiently low pH—below their hydrolysis pH. Sulfuric acid is commonly used, primarily because of its low cost. Oxidized uranium is also soluble in ammonium carbonate solutions, and this lixiviant is used when the uranium ore contains limestone, dolomite or other major acid consuming gangue minerals.

Chemical oxidation of the economic minerals, or other minerals in the ore, is often required to render them soluble. Hydrogen peroxide is often used for this purpose in uranium leaching. Although oxygen is required to solubilize gold in cyanide leaching, the amount is small. For most heap leaching applications where ore is free of sulfides and organic material, oxygen dissolved in the leach solution is adequate. Leaching sulfide or carbonaceous ores is another matter. Large amounts of oxygen are required to oxidize sulfide minerals and for many ores and mine wastes air is the only affordable source of oxygen. Furthermore, the solubility of oxygen dissolved in aqueous solutions is insufficient for commercial production rates. Hence, these leaching systems must have both the solution phase and the air phase present and flowing through the ore mass being leached, a case of **two-phase flow.**

Because of oxygen's low solubility near room temperature, leaching of sulfides and other minerals requiring oxidation would be very slow except for the presence of ferric ions. Fortunately, iron is a ubiquitous element in the earth and most nonferrous ore mineral assemblages. Ferric ions are often present in the ore leaching solution as the primary oxidant. However, the regeneration of ferric ions (from the ferrous ions resulting from mineral oxidation) is kinetically very slow without the assistance of *Thiobacillus ferrooxidans*. These bacteria catalyze the oxidation of both ferrous ions and sulfide minerals. Thus, **biooxidation** of minerals is an important aspect of many solution mining applications. The role of bacteria and bacteria products such as enzymes has expanded into many aspects of solution mining, including environmental treatment of spent solutions, waste water, and hazardous residues as well as mineral oxidation. **Biohydrometallurgy** has recently evolved as a new field of research and industrial practice, which has been exhaustively reviewed in a text by Rossi (1990) that includes over 1,600 references.

IMPORTANCE OF SOLUTION MINING

When technically feasible, the specific treatment cost of solution mining can often be substantially lower than any other approach. Consequently, as lower grade ores are being mined, solution mining is often the only available

Table 1.2   Importance of Solution Mining for USA Selected Metal/Minerals.

Metal or Mineral	Approximate Primary Production
Gold	35%
Silver	25%
Copper	30%
Uranium	75%
Common Salt	50%
Potash	20%
Trona	20%
Boron	20%
Magnesium	85%
Sulfur	35%

route and its use is rapidly expanding. Solution mining ore in heaps and leaching mine waste dumps are well matched to excavation (mining) of bulk ore deposits using large-scale surface mining equipment, which has evolved during the last few decades to provide remarkably low specific mining costs, sometimes less than one US dollar per tonne of ore (1 tonne = 1 metric ton = 1 Mg).

Solution mining is already a major source of several metals and minerals. The author's estimates of the percentage of the primary production attributed to solution mining in the United States are shown in Table 1.2. These estimates are in part based on the U.S. Bureau of Mines Mineral Commodity Summaries. In 1990, the added value of solution mining operations in the western United States was approaching two billion dollars. This figure does not include the value or equivalent cost of associated conventional mining operations to provide ore for leaching in heaps and mine dumps, nor the value of subsequent metal separation operations such as solvent extraction, electrowinning and metal refining. The magnitude of solution mining in the western United States is now easily greater than that of underground hard rock mining of non-fuel minerals, and it is expanding rapidly. Many low grade gold mines, opened in the last decade and operating profitably, would not be possible without the low-cost leaching of ore in heaps.

SHARPENING OUR INTUITIVE UNDERSTANDING OF LEACHING

Let us begin with a simple leaching system and a few experiments the results of which we can easily comprehend, and even perform without

benefit of a laboratory. This might be called "the kitchen series." Consider an event that we are all familiar with—dissolution of sugar in a cup of coffee; or to be more observable, dissolution of sugar in a cup of water. The system is simple because:

— The solubility of sugar in water is very high and unlimited at least with respect to the usual teaspoon of sugar in a cup

— No chemical reaction with another solute or component in water is required to obtain dissolution

— There are no interfering solids, at least yet, assuming we use nominally pure sugar.

For sugar in each of the following four forms, rank the required time (1 through 4 with 1 the least time and fastest rate) to completely dissolve one gram of sugar in a cup of water at room temperature:

powdered sugar   ____

rock candy   ____

granular sugar   ____
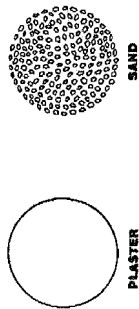
cubed granular sugar   ____
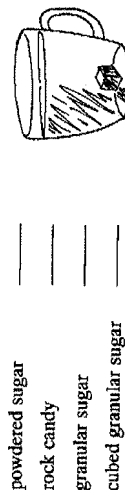
This may be obvious to you, but if not, try the experiment. What will be the trend in results if we use boiling water for each of the four sugars? What did we learn from this—or did we already know it? Mineral particle size is important in leaching, with smaller mineral grains leaching faster than coarser mineral grains; and heat usually accelerates the rate of leaching.

Now consider two series of experiments, each with powdered sugar, granular sugar and 1 mm rock candy, sized by sieving. In the first series, three 20 g spheres of plaster of paris are formed; each contain 0.20 g (1 wt pct) of one of the sugars uniformly mixed with dry plaster prior to adding a little hardening water and forming the sphere.

The second series of experiments are made by forming three identically sized spheres using coarse sand with a very small amount of glue in a volatile solvent as a binder, just enough to hold the sand grains together.

After the spheres have dried and hardened overnight, obtain six large cups or beakers, place one of the spheres in each and fill it with water. The question is which spheres will permit faster sugar extraction? A taste test of each mug at intervals of time will allow you to rank each of the six spheres with respect to the rate of sugar extraction using only the following allowed answers: too slow to taste, slow, slowest, fast, faster, fastest.

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PLASTER   SAND

plaster of paris with powdered sugar

plaster of paris with granular sugar

plaster of paris with rock candy

sand sphere with powdered sugar

sand sphere with granular sugar

sand sphere with rock candy

Hint: the microporosity of the sphere composed of cemented sand grains is higher than the microporosity of the plaster of paris.

As shown in Fig. 1.1, **fractional extraction** increases with leaching time but the **rate** of extraction declines as the solute has farther to travel to escape the plaster or sand spheres (and the rock matrix in ore leaching), and the concentration **gradient**, driving diffusion, decreases.

The fractional extraction rate is expected to decrease as the sphere size increases.

Next, imagine the experiment sketched in Fig. 1.2. A comparison of the results from two similar experiments but with a distinctive difference. Identical spheres of powdered sugar mixed into coarse sand are used in each experiment. In both experiments the spheres are mounted on a pedestal inside a vertical glass tube. In the first experiment the tube is flooded with water that flows past the sphere at a velocity of 0.1 mm/s (call it a superficial velocity for the process engineers). In the second experiment water drips from an orifice immediately above the sphere onto the top of the sphere and then runs off, simulating a percolation leaching experiment. The volumetric water flow rates are identical in each case. Which experiment, if either, will yield the faster sugar extraction? The correct answer is: because water wets both spheres there will be little or no difference. Percolation leaching may be a little faster for sufficiently small spheres because of the higher liquid film velocity adjacent to the sphere's surface.

Next, repeat the prior experiment comparing flooded leaching and percolation leaching except thoroughly inundate the surface of each sand
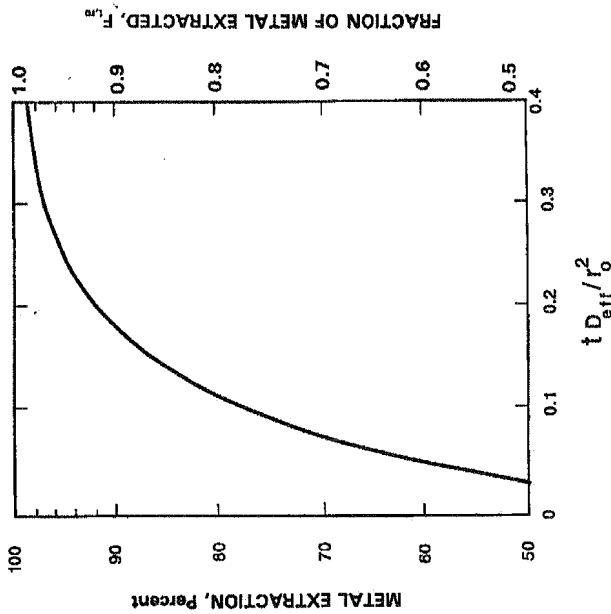

Introduction

Figure 1.1. Fractional extraction of completely dissolved solute from a porous sphere (Crank, 1956).

sphere with hair spray **before** beginning the comparative leaching experiments. That's right, common hair spray. According to the can in my wife's bathroom, hair spray contains organic solvents, methacrylates, isostearic hydrolyzed animal protein and other polymers—in other words, greasy stuff. If you use enough hair spray it should prevent any leaching of the sugar.

What are the factors that determine the rates of sugar extraction in these various cases? Consideration of these experiments suggests the following:

(1) The sugar (mineral) must be soluble in the water (solution).

(2) The rate of dissolution may depend on the sugar (mineral) grain size.

(3) Sugar (mineral) cannot be extracted from a sphere (rock), such as plaster of paris, that has no open microporosity to permit entry of water (solution) into the sphere (rock) and access to the sugar (mineral) grain.

(4) Sugar (mineral) cannot be extracted if the water (solution) does not **wet** the rock and enter the micropores by capillary action; this is a function of surface energy and viscosity; hair spray coated the sphere with material that prevents water from wetting and entering the capillaries.

Other factors affecting extraction but not discovered in the preceding experiments are: (5) sphere (rock) size, (6) ability of solutions to flow by the sphere (rock), sweep away dissolved mineral and avoid saturation at the sphere (rock) surface, and (7) the total amount of sugar (mineral) in the sphere (rock).

Consider the simplified case of a small amount of sugar **disseminated** uniformly within a porous sphere of cemented sand grains. As water enters the pore space, the amount of sugar present is so limited that all of it quickly dissolves. Post examination of the sectioned wet sphere would show no evidence of sugar grains. How does the dissolved sugar, contained in
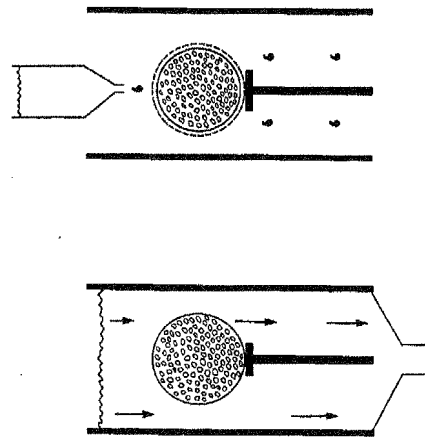

Figure 1.2. Sugar extraction from porous spheres by flooding (left) and percolation (right) leaching.

water-filled micropores within the sphere, exit the sphere? It occurs by ordinary chemical diffusion and not by flow. The solution inside the rock is stagnant. Diffusion is driven by a sugar solution concentration that is higher inside the sphere (rock) than at its surface. Flow only becomes an important transport process once the dissolved material is out of the sphere (rock); then, soluble sugar is swept away by the solution flowing around the sphere (rock). In the case of percolation leaching this is a slowly flowing film on the surface of the sphere (rock).

MODELING EXTRACTION RATES CONTROLLED BY CHEMICAL DIFFUSION

For most mineral leaching systems, fragmented rocks are roughly equidimensional and can be adequately approximated as spheres. Obviously this would not apply to asbestos or other acicular mineral morphologies, but these are rarely encountered in commercial solution mining systems.

The spherical approximation simplifies a mathematical description of transport processes within the rock, using one-dimensional polar coordinates. Fracture patterns in an ore body useful for *in situ* leaching often do not have a preferred orientation and can be similarly approximated. However, the ore mass will have a wide **distribution** of rock sizes from giant boulders (in the case of run-of-mine ore and mine subsidence) to very fine particles. Crushing prior to heap leaching eliminates the boulders and leaves a smaller maximum size, typically about 20mm, but the rock size distribution will remain wide, with the fractional mineral extraction from the small particles occurring much more rapidly. This situation is usually modeled by dividing the ore mass into a histogram of several (often a dozen) discrete rock sizes, with each size described and simulated by a separate numerical subroutine.

Conventional metallurgical and mineral extraction processes are normally conducted using ground ore to accelerate reactions within process vessels of limited size with reaction times measured in seconds to minutes, and occasionally a few hours. Solution mining processes usually occur over much longer periods. Rather than a few tonnes of material in the

reactor, many thousands and even millions of tonnes are typically involved. With solution mining, the mineral dissolution process (commonly a heterogeneous chemical reaction between the solution and mineral grain) and the internal rock pore diffusion process are usually slower than transport processes outside individual rocks. Therefore, these two slow-step processes tend to govern the overall rate of extraction.

Consider our final sugar example: a simplified case of a **small amount** of powdered sugar disseminated in a porous sand sphere that is submerged in water. As water enters the micropores of the sand sphere, the small amount of very fine sugar quickly dissolves. Because a limited amount of sugar was used, all of it dissolves without exceeding the solubility limit of the water contained within the rock micropores (pore water); this is our definition of "small amount." Under these restrictive circumstances, the extraction rate is dependent only on diffusion of the sugar solute through the tortuous pore paths within the sphere.

Thus, the leaching extraction model consists of the diffusion equation for a porous sphere with c the local concentration of solute in the pore fluid:

$$\varepsilon \frac{\partial c}{\partial t} = D_{eff}\left(\frac{\partial^2 c}{\partial r^2} + \frac{2}{r}\frac{\partial c}{\partial r}\right). \quad (1.1)$$

The diffusivity, D, will be that for the sugar solute in water. Since diffusivities for dissolved species in water do not vary much, a reasonable approximation at room temperature is $D = 1.75 \times 10^{-3}$ mm²/s (1.5 cm²/day). The diffusivity of the sphere must be modified by the fractional **microporosity**, ε, of the sphere (internal fractional volume of water filled open micropores), and by a factor, τ, to account for the **tortuosity** of the micropores and the resulting greater diffusion path length. Thus, an **effective diffusivity** results where

$$D_{eff} = \frac{D\varepsilon}{\tau}.$$

The rock interporosity is sometimes referred to in the hydrogeological literature as secondary porosity to distinguish it from the intraporosity between rocks in a clastic sediment, which is referred to as the primary porosity. An ore heap can be characterized as a clastic sediment. In this text, with respect to ore heaps, the word "microporosity" is restricted to the interporosity of the rocks, while the intraporosity is termed the "void space," or, on occasion, the macroporosity.

Comparison with experimental and calculated results for diffusion in porous media usually results in a tortuosity factor of τ=2. Note that one

unit of time used to express the effective diffusivity is days. Solution mining is a slow process measured in weeks, months and sometimes years. Periods less than a day are hardly relevant. With standard values for the diffusivity and tortuosity (used throughout this text unless otherwise stated) the effective diffusivity is:

$$D_{eff} = 8.7 \times 10^{-4}(\varepsilon) \quad [mm^2/s],$$
$$D_{eff} = 0.75 \times 10^{-4}(\varepsilon) \quad [cm^2/d].$$

For initial and boundary conditions of a negligible sugar concentration outside the sphere and a uniform initial concentration of dissolved sugar within micropores of the sphere, c_i, the diffusion equation has been solved (Crank, 1956) to yield the following expression:

$$F_{t,r_0} = 1 - \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(\frac{-D_{eff}\,n^2\pi^2 t}{r_0^2}\right), \quad (1.2)$$

where F_{t,r_0} is the fractional extraction of sugar in time t for a porous sand sphere of radius r_0. This infinite series can be adequately approximated as a finite series for computer solution, since the terms in the series quickly become negligible as the index, n, increases. **Figure 1.1 is a dimensionless plot of the relationships expressed by eqn 1.2.**

EXAMPLE PROBLEM

Uniformly sized porous spherical particles containing sugar were leached over a period of one full day, 24 h and 60% of the sugar was extracted. If the leaching time is increased to 5 days, predict the percent of sugar that will be extracted using Fig. 1.1... and without using eqn 1.2.

ANSWER
(1) Find the value of tD_{eff}/r_0^2 at 60% extraction using Fig. 1.1 and a straight edge or ruler:

$$tD_{eff}/r_0^2 = 0.04.$$

(2) If we increase the time by a factor of five, we must increase tD_{eff}/r_0^2 by a factor of five, hence:

$$tD_{eff}/r_0^2 = 0.20.$$

(3) Again using Fig. 1.1 and a straight edge, find the percent extraction:

$$\text{Answer} = 92\%$$

Note that several parameters needed to solve the problem with eqn 1.2 were not given (rock microporosity and rock radius), yet with Fig. 1.1, you can solve the practical problem. While you don't know the values of microporosity and radius, you can, with the given data coupled with Fig. 1.1 defines the value of D_{eff}/r_0^2. Whenever you have a set of conditions definable by Fig. 1.1, you can change a variable, such as time in this problem, and find the complimentary variable. You can change more than one variable if you know the initial values of those variables. For example, you could change both sphere microporosity and sphere radius to new values and compute its effect.

Continuing with this problem, what is the required time to obtain 60% extraction if the sphere radius is tripled. Answer: Because of the radius squared effect D_{eff}/r_0^2 will be $1/(3)^2$ times its former value (i.e., one-ninth). Therefore the time to obtain the *same* percent extraction must increase from one day to nine days.

The variables, time, percent extraction and sphere size are easy to measure in a laboratory experiment. Microporosity, and therefore D_{eff} are more difficult, but not impossible. Normally in doing laboratory work it is most useful to scale from one set of conditions to another using Fig. 1.1.

Recognize that the fraction reacted, F_n, is a function of $1/r_0^2$. Hence, doubling the rock radius, r_0, increases the time to obtain the same fraction extracted by four.

Figure 1.1 is a **dimensionless parametric process design curve** for a fairly simple leaching system. Dimensionless parametric design curves for more complex ore leaching systems will be introduced later in this text.

If desired, concentration profiles of sugar within the sphere can be computed by solving the diffusion equation for the initial and boundary conditions (Crank, 1956),

$$\frac{c_i-c}{c_i}=1+\frac{2r_0}{\pi r}\sum_{n=1}^{\infty}\left(\frac{(-1)^n}{n}\sin\left(\frac{n\pi r}{r_0}\right)\right)\exp-\left(\frac{D_{eff}n^2\pi^2t}{r_0^2}\right). \quad (1.3)$$

Figure 1.3 schematically shows the sugar concentration within the porous sphere under four conditions: (a) before the sugar containing sphere is submerged into the water (no dissolution of sugar), (b) immediately after submergence and water entry into the micropores causing "instantaneous" dissolution [$time=t_0$], (c) a later time interval t^+, and (d) a still later time interval t^{++}.
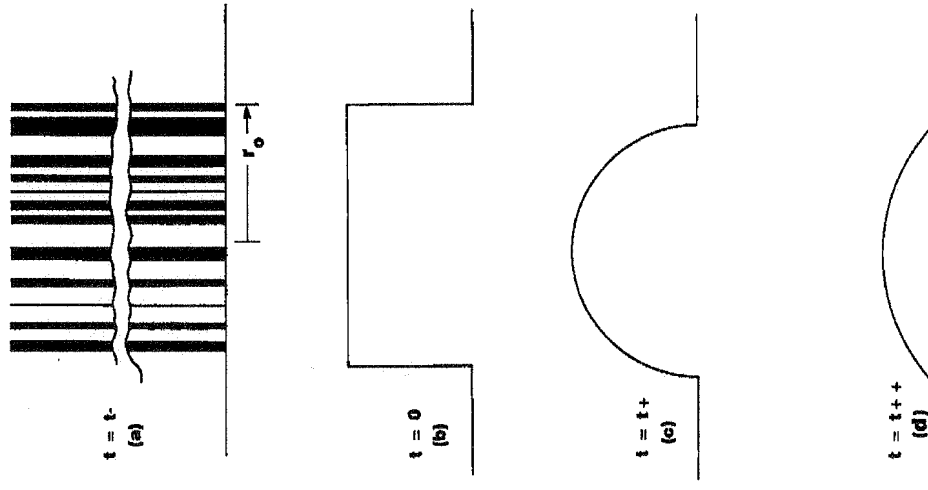
Figure 1.3. Concentration profiles (schematic) across a porous sphere at four time intervals, before and during extraction of a solute.

PROBLEMS

1. Provide your answers to all of the questions posed in this chapter on the dissolution and extraction of sugar contained in spherical solid bodies.

2. Ninety percent of the solute is extracted from a porous sphere in 10 days. How many days are required to obtain only 75% extraction? What is the time to extract 75% from a sphere of the same size with a 25% greater microporosity? Hint: Use Fig. 1.1 directly rather than cumbersome eqn 1.2.

3. Estimate the **initial** internal sphere microporosity in the preceding problem, with 10 days to extract 90%, if the sphere diameter is one inch (2.54 cm).

4. Estimate the time to obtain 98% extraction of sugar for a sphere with the same microporosity if its diameter is increased to four inches (10.16 cm).

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TWO

Heap Leaching Gold (Silver) Ore —Theory

Enough of sugar; does an important mineral leaching extraction system correspond to the simple example of the previous chapter? Yes; and it's a more exciting commodity—GOLD.

DISSEMINATED GOLD ORE DEPOSITS

Disseminated gold deposits, sometimes referred to as Carlin-type deposits, are the basis for most of the gold mining industry in the United States. When oxidized by nature, these ore deposits are readily heap leached; the gold is present as free gold particles, one micron (10^{-6} m) or smaller, that are generally not visible except by scanning electron microscopy. The gold, present in concentrations often less than 3 ppm, usually is hosted in sedimentary rocks. Rock microporosity is usually low but open, and with the exception of some highly silicified rocks, the gold is accessible through micropores and microfractures. However, there are jasperoids of acceptable gold grade that cannot be mined and heap leached because of their low open microporosity. This is caused by a high degree silicification that has occurred after or concurrent with gold deposition and blocks the micropores. These ore deposits are usually associated with ancient hot springs.

Much of the disseminated gold is believed to have been originally deposited as blebs occluded within pyrite or arsenopyrite grains and, therefore, not originally accessible to dissolution by cyanide solutions. However, many of the shallow ores are now above the water table and were geochemically oxidized, after metal deposition, to alter the sulfide minerals and render the gold leachable. The unoxidized ores containing sulfides may also contain pyrobitumen, a residue of thermally mature petroleum, or other organic material, indicating deposition under reducing environments. These unoxidized ores are almost invariably refractory to cyanide leaching.

Most of these disseminated sedimentary deposits contain silver, which is sometimes the major economic metal. Heap leaching technology for silver is essentially the same as for gold.

Heap leaching is not useful for all gold ore deposits. Gold particles are dissolved very slowly and heap leaching does not work well on placer deposits because the gold grains are too large. Sulfide and arsenides occlude the gold particles so that cyanide cannot reach them. Organic material in ore can be a sink for adsorbing the gold cyanide complex. Consequently, in these carbonaceous ores, the gold is solubilized but not removed from the ore mass. Gold present as tellurides is less common but very difficult to leach with cyanide solutions. High cyanide losses and solution fouling can occur when significant amounts of copper, arsenic, iron and other cyanicides are present.

All ores should be evaluated for cyanide gold extraction and cyanide consumption in bottle roll or agitation leaching tests. If these tests are successful, follow them with column testing to simulate heap leaching behavior before proceeding with a new heap leaching project. Nevertheless, the following theoretical discussion is a useful adjunct to ore testing and leaching process understanding.

GOLD LEACHING CHEMISTRY

Gold particles are oxidized and solubilized in the presence of basic cyanide solutions:

$$4Au + 8CN^- + O_2 + 2H_2O = 4Au(CN)_2^- + 4OH^- . \qquad (2.1)$$

This is an electrochemical oxidation reaction that proceeds only because of the great stability of the gold cyanide complex. Oxygen is required for gold dissolution and supplied by air sparging in the leaching of milled ore.

But, the air present in percolation leached heaps is usually adequate because of the small amount of gold present and the limited need for oxygen. Unlike copper sulfide mineral leaching (discussed in a later chapter), the oxygen dissolved in the initial cyanide solution wetting the ore and penetrating rock micropores at saturation is usually sufficient to dissolve all of the gold in the rock. Computations by Wadsworth (1996) based on only the dissolved oxygen at 7 ppm in the pore solution for a Carlin type ore with a measured internal microporosity of 0.036 (3.6 vol pct) indicate a gold dissolution capacity of about 0.07 opt (2 g/tonne); see Fig. 2.1. Furthermore, residual oxygen in the air within a heap, assuming 20 vol pct air void space after solution soaking, is at least two orders of magnitude greater than the amount of oxygen required to dissolve all of the gold typically present in heap leached gold ores.
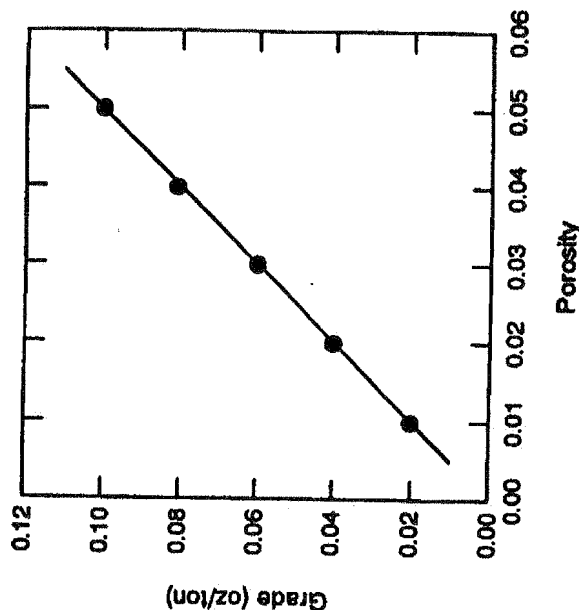

Figure 2.1. Maximum gold grade dissolvable by oxygen in solution saturated micropores of a gold ore (Wadsworth, 1996).

However, the presence of small amounts of sulfide minerals and organic material can compete with gold for the oxygen in some ores. Consequently, on occasion low residual levels of dissolved oxygen in the pregnant liquor draining from the heap will be encountered, and the lower oxygen concentration in the leach solution will retard the rate of gold extraction from the ore heap. When oxygen must diffuse into the micropores from outside the ore rocks, there is a small retardation on the gold cyanide complex diffusion out of the rock, which is normally the rate limiting step and described in the next section.

Wadsworth (1996) also examined limitations on cyanide diffusion into the solution-filled rock micropores for a case where the micropores of a wet ore are initially filled with water without cyanide and later exposed to the cyanide solution when heap leaching begins. Because concentrations of cyanide in the leaching solution, typically 50–200 ppm, are much higher than the oxygen saturation limit of 7 ppm, this process is much faster and would account for gold dissolution in hours rather than many days. In a sequence of transport and chemical reaction steps the slowest step will be the "bottleneck" and is the step that limits the overall rate. Because cyanide diffusive transport is a faster process, due to its much higher concentration, it is not rate limiting.

Further details of gold hydrometallurgy are covered by Burkin (1966) and Dorr (1950). Practice improvements are covered by Kudryk (1984) and Osseo-Asare and Miller (1982). The chemistry of silver leaching with cyanide is similar to that of gold:

$$4Ag + 8CN^- + O_2 + 2H_2O = 4Ag(CN)_2^- + 4OH^-. \quad (2.2)$$
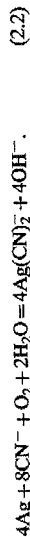
MODELING DISSEMINATED GOLD ORE
HEAP LEACHING EXTRACTIONS

Fortunately, water is the wetting fluid for nearly all rock minerals. During heap leaching, cyanide solutions trickle down over the wetted rocks with solution entering the micropores by capillary action. Because the gold particles are very fine and sparse, the accessible gold located in open micropores and fissures of the rocks is quickly dissolved. Once the soluble gold diffuses out of the rock, it is fairly quickly washed from shallow ore heaps that have good permeability. Washing ore heaps will be treated more thoroughly in a later chapter, but for shallow heaps with high uniform permeability this process is mostly completed in a very few days. Thus, fractional extraction, F_t, is reasonably approximated by the diffusion component of

the process, eqn 1.2 (Bartlett, 1974). However, it is worth emphasizing that this is an estimate of the **fraction** extracted based on only the total extractable metal, which is the free gold accessible to the leaching solution in micropores of the rocks. Rarely is all of the precious metal contained in ore rocks extractable. Often gold has a higher extractability (percentage) than does silver in the same ore because, in part, silver more easily forms refractory mineral compounds.

Assuming a negligible concentration outside the rock because of efficient washing, the estimated soluble gold concentration profiles in a 20 mm diameter rock, calculated from eqn 1.3, are shown in Fig. 2.2 for various times after leaching has started. Calculations for this specific example were based on an assumed rock microporosity of five percent, $\varepsilon = 0.05$. Concentration profiles will be lower, at the same leaching time interval, for smaller rocks.

The time-dependent fractions extracted for 20 mm through 200 mm diameter rocks, each with five percent microporosity, are compared in Fig. 2.3, based on eqn 1.2. Rocks larger than 50 mm show insufficient extraction in the time covered by this figure, four weeks. Uncrushed ore from an open pit mine will usually contain a significant fraction of rocks greater than 200 mm, and a plot of fractional extraction versus log time, shown in Fig. 2.4, amply demonstrates that much longer times are needed to complete extraction from the bigger rocks.
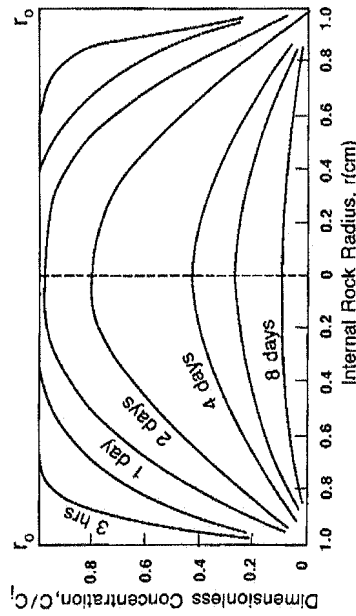

Figure 2.2. Soluble gold concentration profiles in a 20 mm diameter rock with 5% microporosity at times shown after beginning of heap leaching; eqn 1.3.
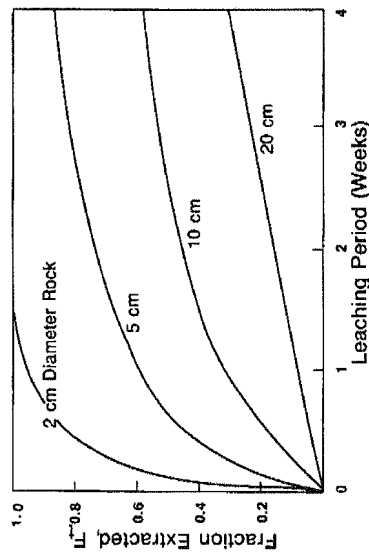
Heap Leaching Gold (Silver) Ore—Theory

Figure 2.3. Time dependent fraction extracted for heap leaching gold from monosize rocks with 5% microporosity and the rock diameters shown, eqn 1.2.
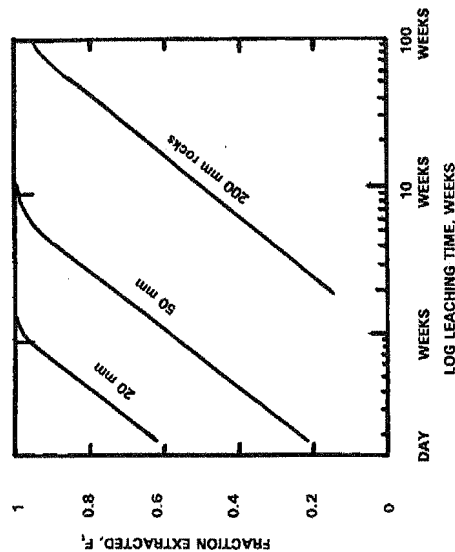

Figure 2.4. Fractional extraction versus log time for selected rock diameters; eqn 1.2.

Figures 2.2 and 2.3 indicate that for reasonably porous ore crushed to −20 mm, most of the gold will be extracted in one or two weeks of heap leaching.

A lowered microporosity can increase the required time for leaching, even when all of the gold is **open pore accessible**. For most mineral deposits, as the rock microporosity declines increasing amounts of precious metal are locked away and ultimate extractions also decline. Reduced microporosity adversely affects fractional extraction. Results for 20 mm rocks are shown in Fig. 2.5.

Dividing the crushed ore size distribution into a few discrete screen sizes, each weighted by its mass fraction of the total, and with extraction calculations using eqn 1.2 performed on each group yields the time dependent fractional extraction, F_t, for the ore heap:

$$F_t = \sum_{y=1}^{Y} F_{t,y}(N_y)_b \qquad (2.3)$$

$$1 = \sum_{y=1}^{Y} N_y, \qquad (2.4)$$

where N_y is the mass fraction of rock group with size r_0 indexed to y.
The fractional extraction as a function of leaching days (time from first appearance of leach solutions draining from the heap) was estimated for
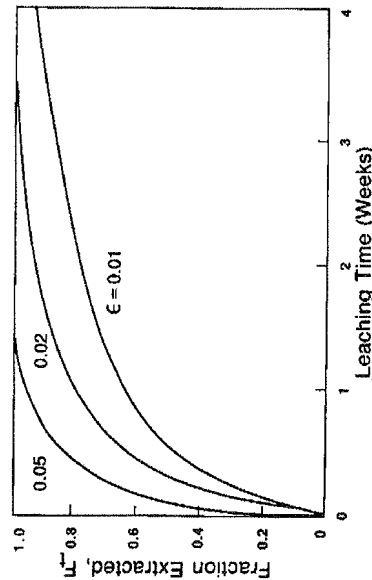

Figure 2.5. Effect of rock microporosity on estimated fractional gold extraction from 20 mm diameter ore rocks, eqn 1.2.

a **distribution** of rock sizes, using the preceding equations, eqn 1.2, and the largest rock size in each size range. The calculated results for a specific case are shown in Fig. 2.6. Extraction is faster for the size distributed rocks than for 20mm monosize rocks because of the smaller rocks that are present. This conforms with gold ore heap leaching observations, at least when the heaps are not too high. In practice, a few days to soak the cyanide solution into the ore mass (while simultaneously dissolving most of the gold in place), a week or two for diffusion, and a final few days for washing soluble gold through the low permeability areas of the heap
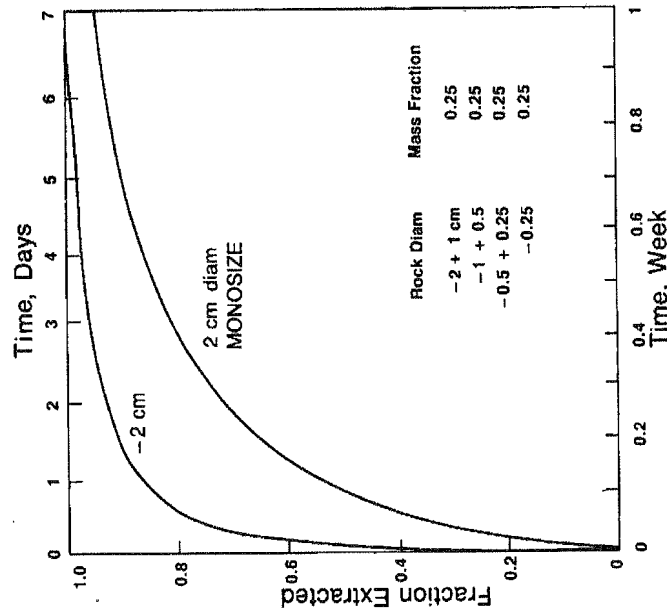

Figure 2.6. Time dependent fractional extraction of gold by heap leaching ore with 5% microporosity and the indicated −20 mm rock size distribution.

should do nicely for shallow ore heaps. When crushed ore is emplaced, heap leached and removed from a reusable impervious leaching pad, the duration (forecast by Fig. 2.4), shows good agreement between this simple leaching model and heap leaching practice at gold and silver mines. Leaching periods of one week to several weeks are usually used with crushed ore, including crushed ore that has been agglomerated. Tighter ores (low microporosity) require longer periods and, as mentioned, some highly silicified jasperoids cannot be heap leached.

Run-of-mine ore, with rock fragment sizes much greater than 20mm, will require much longer periods. When gold heap leaching run-of-mine ore is practiced, the ore is usually permanently stacked, with a series of layers, sometimes referred to as "lifts." Each lift is leached before the next lift is emplaced. Extraction from the larger rocks in buried lifts will continue as the leaching solution trickles down over many months and years.

ESTIMATING FRACTIONAL EXTRACTION OF DISSOLVED SOLUTE FROM A DISTRIBUTION OF ORE ROCK PARTICLE SIZES USING A DIMENSIONLESS EXTRACTION CURVE

There have been several studies of the particle size distribution resulting from crushing ores and other brittle solids. It has been observed that a logarithmic plot of the cumulative fraction of material finer than a given size versus the corresponding size is usually a straight line with a slope, m, of one, or slightly less. Different, but similar equations have been used to express this relationship, including the well established Gates–Gaudin–Schuhmann (GGS) equation (Schuhmann, 1960):

$$Y(r_i) = (r_i/r_s)^m \qquad (2.5)$$

with: $0.7 < m \leq 1.0$, where $Y(r_i)$ is the cumulative fraction finer than size r_i and r_s is the radius of the largest rock in the broken ore.

The GGS equation has been coupled with the diffusion equation (eqn 1.1) to develop a numerical relationship for a distribution of particle sizes that is analogous to the dimensionless analytical relationship for monosize particles that was plotted in Fig. 1.1 (Bartlett, 1971). This leads to a relationship in which F_t depends on $tD_{eff}/(r_s)^2$. However a band in the plot of F_t occurs because of the variation in the Gates–Gaudin–Schuhmann breaking function, m, in eqn 2.5, with the boundaries of the band corresponding to the extremes in the breaking function, viz. $m=1$ and $m=0.7$. While the value of m can be determined from a log plot of the sieve analysis data, an additional operational problem and error may arise in estimating the

largest particle radius, r_*, by extrapolation from a sieve analysis of the ore sample. It is often easier and more precise to use a sieve analysis to accurately determine a particle diameter for which the undersize mass of particles is equal to a percentage of the total ore sample mass, but less than 100%. Commonly, the ore sieve analysis is expressed this way using a d_{80}, which is the rock diameter at which the undersize particles comprise 80% of the total sample mass. With respect to the Gates–Gaudin–Schuhmann distribution when the breaking function is $m=1$, then from eqn 2.5, $d_{80}/2=0.8r_*$. However, when $m=0.7$ using eqn 2.5, $d_{80}/2=0.727r_*$, which is only about 91% of the d_{80} at $m=1$. This results because there are proportionately more fine particles and the d_{80} shifts to a smaller size as the breaking function shifts from $m=1$ to $m=0.7$, while both are at the same maximum particle size.

Figure 2.7 is a dimensionless plot of the percent extraction of metal, which is $100F$, versus $tD_{eff}/(r_*)^2$ when $m=1$. Clearly, at $m=1$, $d_{80}/1.6$ can be substituted for r_*:

$$r_* = d_{80}/1.6. \qquad (2.6)$$

Fortuitously, and most important, when $d_{80}/1.6$ is *defined* as r_* at other values of the breakage function within the range $0.7<m\leqslant1$, and compared with the correct extraction curves computed (Bartlett, 1971) there is a fairly good correlation. It is adequate to the imprecision of sampling ore and characterizing all of the ore, including r_*, from the sieve analysis obtained from the sample.

The definition of eqn 2.6 provides a convenient and practical method of analyzing the extent of metal extraction over time, using the single design curve in Fig. 2.7, with either r_* or d_{80} obtained from an ore sample sieve analysis characterization. Be cautioned that selecting either greater or lower characterizing ore particle diameters than d_{80} leads to distortion from the correct results at $m<1$, which becomes significant as the selected characterizing size variation from d_{80} increases.

Figure 2.7 is directly useful in estimating fractional extraction, F_b as a function of leaching time for any value of d_{80} and $0.7<m\leqslant1.0$, if the effective diffusivity is known. However, an accurate value of the internal microporosity, ε, is needed for D_{eff}, and this is difficult to obtain. While internal rock microporosity measurements can be made on small samples, it is difficult to determine if they are representative without making a very large number of expensive measurements. This is essentially a rock internal microporosity sampling problem.

Nevertheless, Fig. 2.7 can still be very useful, because it can first be used to determine an empirical value of D_{eff}, for example from the results
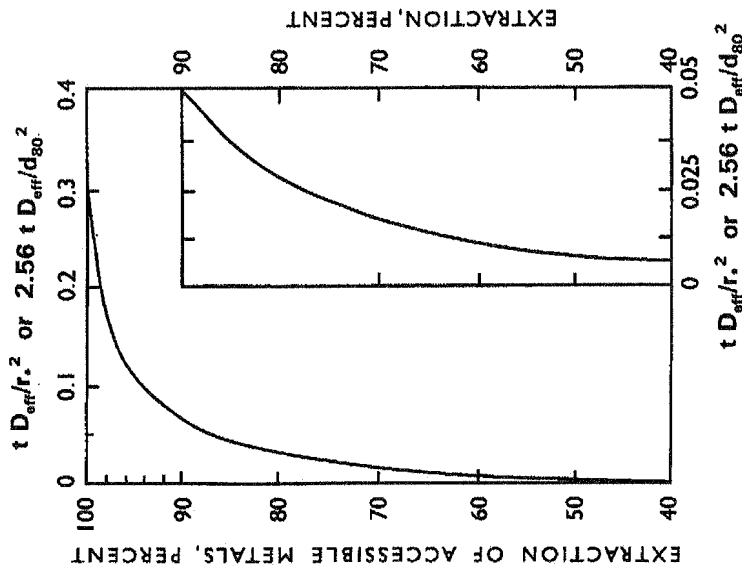
Figure 2.7. Fractional extraction design curve for completely dissolved solute from a multisize aggregation of rocks, as a function of effective diffusivity, D_{eff}, and the d_{80} or r_* in the rock size distribution.

of column ore leaching tests. This is done by comparing an experimental fractional extraction obtained at the corresponding leaching time: Ideally, several experiments will be performed to obtain a best value of D_{eff} by averaging the results:

$$D_{eff}=[\mathrm{Abs}(F_t)]\,[(d_{80}/1.6)^2/t_L], \qquad (2.7)$$

where Abs(F_j) is the abscissa value obtained from the design curve of Fig. 2.7 that corresponds to the fraction extracted, F_j, at leaching time, t_L.

After a best value of D_{eff} has been determined, it can be used to estimate the time required to obtain a desired fractional metal extraction, again using Fig. 2.7. Conversely, for a specified leaching time, the percent of metal extracted can be estimated.

Furthermore, with a reliable value of D_{eff} determined, a change in the ore size distribution, e.g., from more or less crushing to a new value of d_{80}, can also be accommodated with these relationships to compute its leaching extractions with time.

Caution: The dimensionless group in the abscissa (X-axis) of Fig. 2.7, $t D_{eff}/(d_{80}/1.6)^2$, must be in consistent units. For example if D_{eff} is given in m^2/s, then the characterizing rock size, d_{80}, must be in meters and the time must be in seconds.

There are two principal problems associated with the use of Fig. 2.7 to determine the leaching rate characteristics of gold and silver ore, or any other ore where transport by diffusion after rapid dissolution of *all* of the mineral occurs governs the rate of mineral extraction. First, some of the mineral may be locked in plugged micropores and unaccessible to the leaching solution at the planned crush size; the gold is not adequately liberated. Second, a finite amount of time is required for the leaching solution to fully penetrate the internal micropores of the rocks and dissolve the gold, causing an induction period or delay before soluble gold appears in the leachate. While the rate of gold dissolution of micron sized gold particles is relatively fast, hours to several days will be required depending on the gold particle size. This can extend to much longer times, including weeks and months if nuggets are present. When gold particles larger than a few microns are in the ore they are tantamount to not fully accessible gold within the time of usual heap leaching cycles.

Figure 2.8 displays extraction versus leaching time for a large gold ore sample crushed to −2.5 cm (−1 in), thoroughly blended and divided into fifteen equal portions each of which was used in a cyanide column leaching experiment. The gold in this hypothetical ore is not visible under a microscope. Five leaching periods were used: 4, 8, 9, 12 and 17 days, with triplicate column experiments run at each period. The range of experimental results at each time period is shown in the graph.

Clearly, these results do not match an overlay of Fig. 2.7. However, if Fig. 2.8 is moved to the right and down, a very good fit results, as is shown in Fig. 2.9. This corrected fit can be explained by the following assumptions: First a two day induction period is required for lixiviant
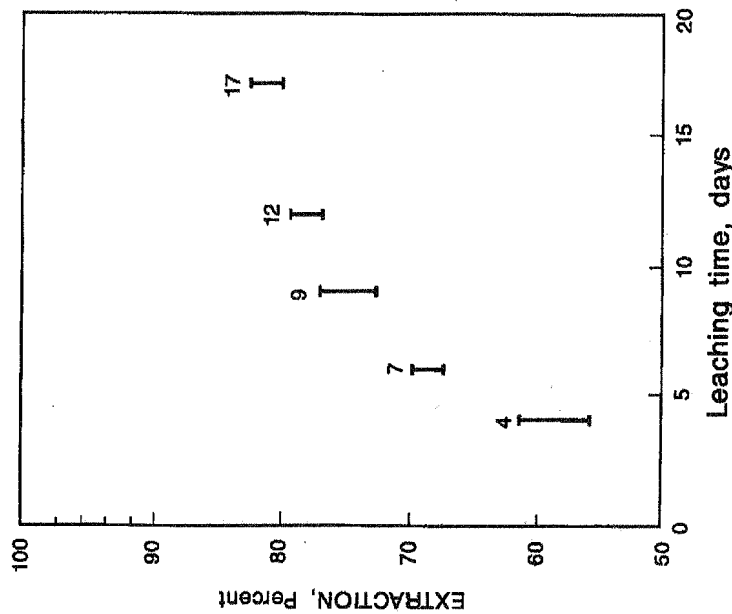
Figure 2.8. Fractional extraction of gold from triplicate cyanide column ore leaching experiments carried out for five time periods.

penetration into the ore and gold particle dissolution, which is reasonable, and second, apparently only about 82% of the gold contained in the ore is accessible to the lixiviant after crushing to −2.5 cm. The remaining gold is presumably locked in micropores and fissures that are sealed. With this corrected fit it is possible to make an estimate of the average internal microporosity in the ore and its effective diffusivity.
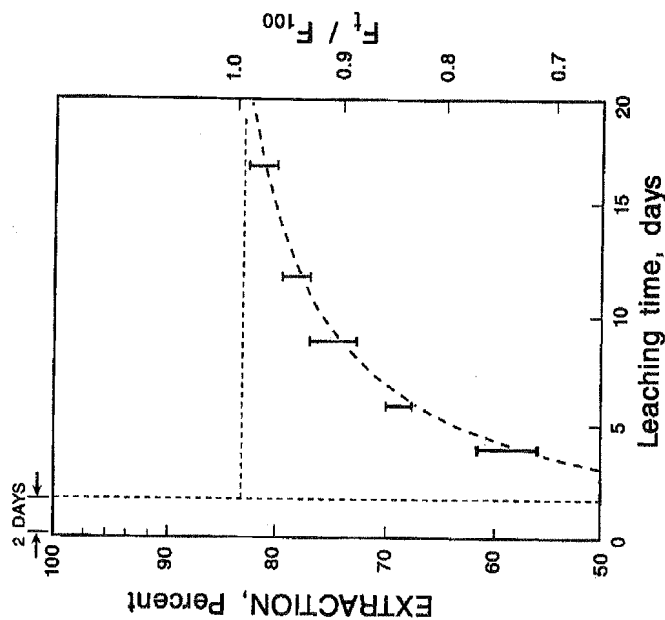
Table 2.1 Silver Extraction by Column Leaching at Various Crush Sizes for a Bolivian Silver Ore Stockpile.

Ore Size	Extraction
−75 mm	15%
−25 mm	44%
−6 mm	64%
−2.36 mm (8 Mesh)	66%
−600 μm	84%
−150 μm	87%

being extracted from the rock to the leaching solution is similar to the concept of liberation of minerals prior to separation (concentration) in mineral processing operations such as flotation. Mineral accessibility often increases as rock sizes decrease. An extreme example of this is shown in Table 2.1, which is a summary of column leaching experiments on a Bolivian silver ore stockpile after crushing to various top sizes. These test results dictated grinding the ore to 600 μm (28 mesh) followed by ore agglomeration before heap leaching. Even then, the late stage leaching rate was very slow and a long leach cycle of 120 days was selected for this heap leaching operation.

Other ore characteristics that often affect valuable mineral accessibility include ore grade, host rock, and the other minerals present in the ore mass.

ROCK PARTICLE LEACHING SIZE VERSUS SIEVE PASSING SIZE

In laboratory ore testing practice, aggregates of monosize particles don't exist. The closest approximation is an aggregate of particles passing one sieve but not passing the next smaller size sieve. The particles will vary in size between the two sieve aperture sizes and it is possible to choose the mean of these to represent the "monosize" particle aggregation. However, leaching transport rates depend on the rock radius squared. Hence for purposes of solution mining it is advisable to use an average of the apertures squared for the squared average aperture,

$$d^2_{a(avg)} = \frac{1}{2}\left(d^2_{a(H)} + d^2_{a(L)}\right). \tag{2.8}$$

Figure 2.9. Matching the data from Fig. 2.8 to the design curve of Fig. 2.7, using a two-day induction period and limiting the accessible mineral to 82% of the total mineral present in the ore.

These data also suggest a further investigation toward improving leaching performance for this ore. For example, will crushing finer than −2.5 cm raise the ultimate possible extraction above 82%?

VALUABLE MINERAL ACCESSIBILITY TO THE LIXIVIANT AND EXTRACTION

The importance of valuable mineral accessibility to the leach solution cannot be overemphasized. The accessibility, or availability, of the mineral

For the standard sieve sizes, where the next larger sieve aperture is $2^{1/2}$ greater, this leads to

$$d_{a(avg)} = 0.866 d_{a(H)} \qquad (2.9)$$

which is slightly larger than the simple mean of the two separating sieve apertures. Computed results of these values are tabulated, with standard sieve sizes, in Appendix Table A-2. This approach can also be used for crushed rock that has been passed through a screen or grizzly. The use of d_{80} in conjunction with the dimensionless design curves of Fig. 2.7 is preferred because it automatically accounts for variations in the rock breaking function. However, it is often difficult to determine a d_{80} for coarse crushed ore and run-of-mine ore. When d_{80} is not available, but the ore has passed a grizzly or screen so that $d_{a(avg)}$ can be computed from the screen size using eqn 2.9, then the following relation is recommended as the best available estimate for use with Fig. 2.7:

$$d_{80} = 0.84 d_{a(avg)} \qquad (2.10)$$

and

$$d_{80} = 0.693 d_{a(H)}. \qquad (2.11)$$

Furthermore, if an estimate of r_* is needed, it can be obtained from eqns 2.6 and 2.11 yielding,

$$r_* = 0.433 d_{a(H)}. \qquad (2.12)$$

EXAMPLE PROBLEM I

Leaching tests of a gold ore crushed to −10 mesh showed that the maximum extraction over an extended period was 90%. Multiplicate column tests of the ore crushed and screened to pass 1-1/2 in yielded an average extraction of 63% in 7 days. Using Fig. 2.7, estimate the leaching time required for this crushed and screened ore to obtain 85% extraction?

ANSWER

(1) Because only 90% of the gold is extractable (10% is locked), the extraction of accessible gold in 7 days is:

63%/0.90 = 70%

and at 85% total extraction the extraction of accessible gold is:

85%/0.9 = 94.5%

(2) Using Fig. 2.7, the value of $tD_{eff}/(1.6/d_{80})^2$ at 70% extraction is 0.016.
(3) Using Fig. 2.7 the value of $tD_{eff}/(1.6/d_{80})^2$ at 94.5% extraction is 0.125.
(4) Because the values of D_{eff} and d_{80} have not changed, the leaching time must increase from 7 days, and do so in proportion to the increase in the value of $tD_{eff}/(1.6/d_{80})^2$; hence:

$$t = 7 \text{ days } (0.125/0.016) = 54.7 \text{ days.}$$

EXAMPLE PROBLEM II

For the given data of the preceding problem, estimate the value of the effective diffusivity and microporosity of this ore.

ANSWER

(1) First, we must determine r_*, and since we don't know d_{80}, we will estimate r_* from eqn 2.12:

$$r_* = \frac{1}{2} d_{a(avg)} = 0.433 d_{a(H)} = 0.433(1\text{-}1/2 \text{ in}) = 0.65 \text{ in}$$
$$r_* = 16.5 \text{ mm} = 1.65 \text{ cm}$$
$$r_*^2 = 2.72 \text{ cm}^2$$

(2) for the given data ($t = 7$ d and $F_t = 0.70$) and this value of r_*,

$$r_*^2/t = 2.7277 \text{ cm}^2/d = 0.389 \text{ cm}^2/d$$

and from the previous problem, $tD_{eff}/(r_*)^2$ is 0.016 then D_{eff} is:

$$D_{eff} = [tD_{eff}/r_*^2] (r_*^2/t) = 0.016 \times 0.389$$
$$D_{eff} = 6.2 \times 10^{-3} \text{ cm}^2/d$$

However, for aqueous solutions,

$$D_{eff} = 0.75(\varepsilon) \text{ cm}^2/d$$

Hence, $\varepsilon = 6.2 \times 10^{-3}/0.75$

$$\varepsilon = 0.0083$$
$$\varepsilon = 0.83 \text{ percent.}$$

MEASURING INTERNAL ROCK MICROPOROSITY, ε

Internal rock microporosity is measured by comparing the mass of a dried rock sample with the same sample first dried and then saturated with an

injected liquid. Drying is conducted at a modest temperature to prevent removal of chemically bound water, e.g. 105°C for 48 hr or more. If total microporosity is sought then pressure injection of mercury using a mercury porosimeter can be used. Pressure forces the mercury into all of the open micropores regardless of pore size. For purposes of heap leaching it is easier and more valid to soak a previously dried sample in water for an extended period of time, typically at least 48 hr. Micropores not filled by this procedure are generally too small to be involved in the leaching process. The volume of the rock sample, including its internal microporosity, is determined from the volume of water displaced upon submergence of the blot-dried but soaked sample. The water soaked sample is blot-dried and immediately weighed. Its mass is compared with the dry sample mass to obtain the mass and thereby the volume of internal water contained in the sample. Comparing the two volumes yields the fractional volumetric microporosity, ε.

PROBLEMS

1. Estimate and plot on graph paper Fraction extracted, F, versus weeks of leaching time for solubilized gold in a disseminated ore with 0.03 microporosity for each of the following monosize ore fragments:
   (a) 2 mm diam. rock,
   (b) 20 mm diam. rock, and
   (c) 80 mm diam. rock.

2. On/off heap leaching of crushed ore with a reusable pad at the New Ophir Mine is providing an average gold extraction that is 80% of the accessible gold in the ore. Using Fig. 2.7, estimate the extraction of accessible gold that will be obtained if the leaching time is *doubled*.

3. For an ore with a d_{80} of 2.10 in, recommend a leaching time to obtain 90% extraction. The internal microporosity is unknown but not expected to be less than 0.005 (0.5%).

4. Using the data presented in Figs. 2.8 and 2.9, estimate the average value of the internal rock microporosity in this ore, which was repeatedly crushed and sieved until all of it passed a one inch *nominal* sieve.

5. An on/off gold heap leaching operation using two crushing stages to produce rock that passes through a two inch screen (nominal) obtains 55% extraction of the accessible gold in the ore. (a) Using Fig. 2.7 and Table A-2, predict the percent extraction of accessible gold that will be obtained if a third crushing stage and larger screen decks are installed

to produce ore passing through a 1 in (nominal) screen. (b) As a safety factor recalculate the estimated percent extraction of accessible gold if the largest rock size is equal to the size of the one inch screen aperture.

6. Estimate the ore specific gravity and microporosity from the following experimental data. The crushed ore was wet screened to remove -10 mesh fines and dried. Then, a dry sample weighing 213.0 g was submerged into a large graduated cylinder containing water, with a corresponding increase in the water level of 81.0 ml after all air bubbles had been released. After 72 hr, the contents of the graduated cylinder were washed out, filtered with a large buchner funnel and allowed to blot-dry by sucking air through the filter cake. The filter cake weight, including the filter paper weighing 1.0 g, was 216.7 g.

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be turned off. Drainage will continue to occur for several days after solution application ceases.

Make-up chemical reagents, added to the barren solution being returned to the ore heap, include water to supplant evaporation losses in dry climates, sodium cyanide, and usually caustic (NaOH) to provide protective alkalinity in a pH range between 10 and 11. Caustic is often preferred over less expensive lime in order to reduce calcium carbonate scaling in the pipelines. Small amounts of proprietary scaling inhibitors are also continuously injected into the returning barren solution. Consumption of caustic is often reduced by adding less expensive lime, in a small fixed amount, to each truck while hauling ore to the heap. Dumping onto the heap provides crude, but adequate mixing and the excess calcium is retained in the heap rather than depositing in pipelines.

Metal recovery occurs either by (1) adsorption on hard-shell activated carbon or (2) zinc precipitation, after purging excess dissolved oxygen, using the Merrill-Crowe process. Both zinc precipitates and metal stripped from the activated carbon are smelted to a doré bullion. Because the metal loading capacity of activated carbon is limited, the economic value of silver loaded carbon is quite modest. For this reason, zinc precipitation is usually selected when an economically significant amount of silver is being extracted from the ore.

HEAP CONSTRUCTION

Heaps are constructed by (1) dumping from haul trucks, (2) stacking with a front-end (wheel) loader, and (3) mechanical stacking using conveyor belts. Two truck dumping methods, (1) over end dumping and (2) stacking, or plug dumping, are illustrated in Fig. 3.2.

The major problem with heap construction using haul trucks is the compaction and extreme loss of permeability in the upper few feet of the heap caused by truck wheel pressure. This is less serious with hard ore, but soft ore will crush and produce a virtually impervious top layer. Because dozers and other track vehicles produce very low ground pressure, they are used to level and rip the surface of the heap, as deeply as possible, after construction and prior to leaching. This breaks up the compaction zone and improves permeability.

Front-end loaders travel on the leach pad surface to stack the ore in a heap. Consequently, the loader does not cause compaction on top of the heap. Depending on their size, front-end loaders can construct heaps from 3 to 5.5 m high.